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Recent progress on the study of the charmoniumlike states*

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In this article, we review the recent experimental studies on the charmoniumlike states, mainly from the e^+e^- annihilation experiments BESIII, Belle, BaBar, and CLEO-c, and the hadron collider experiment LHCb. We discuss the results on the $X(3872)$, the vector Y states [$Y(4008)$, $Y(4660)$, and those in $e^+e^- \rightarrow \pi^+\pi^-h_c$], and the charged charmoniumlike Z_c^- states.

Keywords: charmoniumlike states; exotic states; charmonium; hadronic transitions.

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1. Introduction

In the conventional quark model, mesons are composed of one quark and one anti-quark, while baryons are composed of three quarks [1]. However, exotic hadronic states with other configurations have been searched for and many candidates were proposed [2,3]. These states include glueballs (with no quark), hybrids (with quarks and excited gluon), multi-quark states (with more than three quarks), and hadron molecules (bound state of two or more hadrons). Since a proton and a neutron can be bounded to form a deuteron, it is also believed that other states beyond the quark model must exist.

It is a long history of searching for all these kinds of states, however, no solid conclusion was reached until recently on the existence of any one of them, except deuteron [2,3]. Two statements may well describe the situation as of 2005 when the existence of the $\Theta(1540)$, a candidate of pentaquark state was discussed [4]: “The absence of exotics is one of the most obvious features of QCD” [5], and “The story of pentaquark shows how poorly we understand QCD” [6].

Dramatic progress was made in the study of the exotic states after the running of the two B -factories, i.e., Belle [7] at KEK and BaBar [8] at SLAC. Although

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the two experiments were designed for the study of the B mesons, copious events with charm and anti-charm quark pair were produced due to the unprecedented high luminosity reached at these two experiments. This made the study of the charmonium spectroscopy very fruitful, and since 2003, lots of new states (called charmoniumlike states or XYZ particles) have been observed in the final states with a charmonium and some light hadrons [3, 9–11].

All these states populate in the charmonium mass region. They could be candidates for charmonium states, however, there are also strange properties shown from these states, these make them more like exotic states rather than conventional mesons [3, 10, 11].

The BESIII [12] experiment at the BEPCII collider started data taking in 2009, and lots of data were accumulated at the peak of the narrow vector charmonium resonances like J/ψ , $\psi(2S)$, and $\psi(3770)$, as well as at above 4 GeV, these high energy data make the study of the XYZ states possible [28].

The LHCb [13] experiment at the LHC accumulated 3 fb^{-1} pp collision data at $\sqrt{s} = 7$ and 8 TeV, corresponding to more than an order of magnitude more B decays compared with the BaBar and Belle experiments. This data sample made the improved study of the XYZ states observed in B decays possible [14, 16, 17].

In this review, we present the most recent results on the study of the $X(3872)$ from the B decays and the $Y(4260)$ radiative transition, the Y states from initial state radiation (ISR) processes and from e^+e^- annihilation, and the charged Z_c^- states. The results are from the BESIII [12], Belle [7], BaBar [8], and CLEO-c [18] experiments, as well as the LHCb [13]. The data samples used for the study of the XYZ states collected at these experiments are summarized in Table 1.

2. New information on the $X(3872)$

The $X(3872)$ was observed at the Belle experiment in $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ decays more than ten years ago [19]. It was confirmed subsequently by several other experiments [20–22]. Since its discovery, the $X(3872)$ state has stimulated special interest for its nature. Both BaBar and Belle observed $X(3872) \rightarrow \gamma J/\psi$ decay, which supports $X(3872)$ being a C-even state [23, 24]. The CDF and LHCb experiments determined the spin-parity of the $X(3872)$ being $J^P = 1^+$ [14, 25], and CDF experiment also found that the $\pi^+ \pi^-$ system was dominated by a $\rho^0(770)$ resonance in $X(3872) \rightarrow \pi^+ \pi^- J/\psi$ [27].

The $X(3872)$ was only observed in B meson decays and hadron collisions before. Since the quantum number of $X(3872)$ is $J^{PC} = 1^{++}$, it can be produced through the radiative transition of the excited vector charmonium or charmoniumlike states such as the ψ s and the Y s [26]. Being near $D^0 \bar{D}^{*0}$ mass threshold, the $X(3872)$ was interpreted as a good candidate for a hadronic molecule or a tetraquark state [3], the observation of its large decay rates to $\gamma \psi(2S)$ contradicts expectation of the molecule model [15, 16]. These will be discussed below.

Table 1. Data samples for the study of the charmoniumlike states.

Experiment	\sqrt{s} (GeV)	\mathcal{L} (fb $^{-1}$)	comments
BaBar	10.023	14	$\Upsilon(2S)$
	10.355	30	$\Upsilon(3S)$
	10.580	433	$\Upsilon(4S)$
	10.520	54	off resonance
Belle	9.460	6	$\Upsilon(1S)$
	10.023	25	$\Upsilon(2S)$
	10.355	3	$\Upsilon(3S)$
	10.580	702	$\Upsilon(4S)$
	10.867	121	$\Upsilon(5S)$
	10.520	89	off resonance
	10.75-11.02	28	$\Upsilon(5S)$ scan
BESIII	4.009	0.5	$\psi(4040)$
	4.230	1.1	$Y(4260)$
	4.260	0.8	$Y(4260)$
	4.360	0.5	$Y(4360)$
	4.420	1.0	$\psi(4415)$
	4.600	0.6	$Y(4660)$
	3.81-4.59	1.6	R scan and off resonance
CLEO-c	4.170	0.6	$\psi(4160)$
LHCb	7×10^3	1	pp collision
	8×10^3	2	pp collision

2.1. Observation of $Y(4260) \rightarrow \gamma X(3872)$

BESIII reported the observation of $e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma \pi^+\pi^- J/\psi$, with J/ψ reconstructed through its decays into lepton pairs ($\ell^+\ell^- = e^+e^-$ or $\mu^+\mu^-$) [26]. The analysis is performed with the data samples collected with the BESIII detector taken at e^+e^- center-of-mass (CM) energies from 4.009 GeV to 4.420 GeV [28].

The $M(\pi^+\pi^- J/\psi)$ distribution (summed over all energy points), as is shown in Fig. 1, is fitted to extract the mass and signal yield of the $X(3872)$. The $\psi(2S)$ signal is used to calibrate the absolute mass scale and to extract the resolution difference between data and MC simulation. Figure 1 shows the fit result, the measured mass of $X(3872)$ is $(3871.9 \pm 0.7 \pm 0.2)$ MeV/ c^2 . From a fit with a floating width one obtains a width of $(0.0^{+1.7}_{-0.0})$ MeV, or less than 2.4 MeV at the 90% confidence level (C.L.). The statistical significance of $X(3872)$ is 6.3σ , estimated by comparing the difference of log-likelihood value with and without $X(3872)$ signal in the fit, and taking the change of number of degrees of freedom into consideration.

The Born-order cross section is calculated using $\sigma^B = \frac{N^{\text{obs}}}{\mathcal{L}_{\text{int}}(1+\delta)\epsilon\mathcal{B}}$, where N^{obs} is the number of observed events obtained from the fit to the $M(\pi^+\pi^- J/\psi)$ distribution, \mathcal{L}_{int} is integrated luminosity, ϵ is selection efficiency, \mathcal{B} is branching ratio of $J/\psi \rightarrow \ell^+\ell^-$ and $(1+\delta)$ is the radiative correction factor. The results are listed in Table 2. For 4.009 GeV and 4.360 GeV data, since the $X(3872)$ signal is not significant, upper limits on the production rates are given at 90% C.L. The measured cross sections at around 4.260 GeV are an order of magnitude higher than the NRQCD calculation of continuum production [29], this may suggest the $X(3872)$

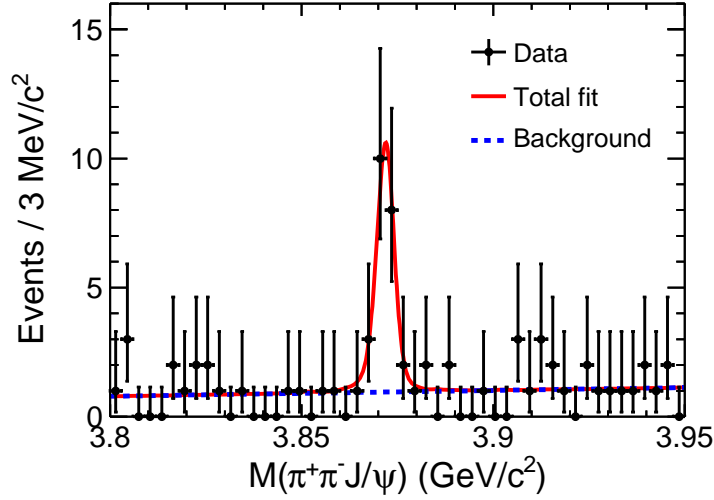


Fig. 1. Fit the $M(\pi^+\pi^-J/\psi)$ distribution observed at BESIII. Dots with error bars are data, the curves are the best fit.

events come from a resonant decays.

Table 2. The product of the Born cross section $\sigma^B(e^+e^- \rightarrow \gamma X(3872))$ and $\mathcal{B}(X(3872) \rightarrow \pi^+\pi^-J/\psi)$ at different energy points. The upper limits are given at 90% C.L.

\sqrt{s} (GeV)	$\sigma^B[e^+e^- \rightarrow \gamma X(3872)] \cdot \mathcal{B}(X(3872) \rightarrow \pi^+\pi^-J/\psi)$ (pb)
4.009	$0.00 \pm 0.04 \pm 0.01$ or < 0.11
4.229	$0.27 \pm 0.09 \pm 0.02$
4.260	$0.33 \pm 0.12 \pm 0.02$
4.360	$0.11 \pm 0.09 \pm 0.01$ or < 0.36

The energy-dependent cross sections are fitted with a $Y(4260)$ resonance (parameters fixed to PDG [30] values), a linear continuum, or an $E1$ -transition phase space ($\propto E_\gamma^3$) term. Figure 2 shows all the fit results, which give $\chi^2/\text{ndf} = 0.49/3$ (C.L.=92%), 5.5/2 (C.L.=6%), and 8.7/3 (C.L.=3%) for a $Y(4260)$ resonance, linear continuum, and phase space distribution, respectively. The $Y(4260)$ resonance describes the data better than the other two options.

These observations strongly support the existence of the radiative transition process $Y(4260) \rightarrow \gamma X(3872)$. The $Y(4260) \rightarrow \gamma X(3872)$ could be another previously unseen decay mode of the $Y(4260)$ resonance. This, together with the transitions to the charged charmoniumlike state $Z_c(3900)$ [31–33], suggest that there might be some commonality in the nature of the $X(3872)$, $Y(4260)$, and $Z_c(3900)$, the model developed to interpret any one of them should also consider the other two. As an example, the authors of Ref. 35 put all these states into a molecular picture to

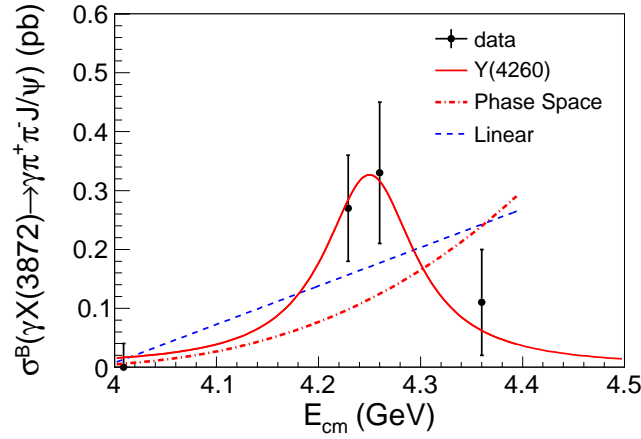


Fig. 2. The fit to $\sigma^B[e^+e^- \rightarrow \gamma X(3872)] \times \mathcal{B}[X(3872) \rightarrow \pi^+\pi^- J/\psi]$ measured by BESIII with a $Y(4260)$ resonance (red solid curve), a linear continuum (blue dashed curve), or an $E1$ -transition phase space term (red dotted-dashed curve). Dots with error bars are data.

calculate $e^+e^- \rightarrow \gamma X(3872)$ cross sections.

Combining with the $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ cross section measurement at $\sqrt{s} = 4.260$ GeV from BESIII [31], one obtains $\sigma^B[e^+e^- \rightarrow \gamma X(3872)] \cdot \mathcal{B}[X(3872) \rightarrow \pi^+\pi^- J/\psi] / \sigma^B(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = (5.2 \pm 1.9) \times 10^{-3}$, under the assumption that $X(3872)$ and $\pi^+\pi^- J/\psi$ produced only from $Y(4260)$ decays. If one takes $\mathcal{B}[X(3872) \rightarrow \pi^+\pi^- J/\psi] = 5\%$ [34], then $\mathcal{R} = \frac{\mathcal{B}[Y(4260) \rightarrow \gamma X(3872)]}{\mathcal{B}[Y(4260) \rightarrow \pi^+\pi^- J/\psi]} \sim 0.1$.

2.2. Observation of $X(3872) \rightarrow \gamma\psi(2S)$

Radiative decays of the $X(3872)$ provide crucial information to understand its nature, especially to check if it is a conventional charmonium or an exotic state.

The transition $X(3872) \rightarrow \gamma J/\psi$ was measured by BaBar [23] and Belle experiments [24]. Evidence for the $X(3872) \rightarrow \gamma\psi(2S)$ was reported by BaBar [15] with a statistical significance of 3.5σ and the ratio of the branching fractions was measured to be

$$R = \frac{\mathcal{B}(X(3872) \rightarrow \gamma\psi(2S))}{\mathcal{B}(X(3872) \rightarrow \gamma J/\psi)} = 3.4 \pm 1.4.$$

In contrast, no significant signal was observed at Belle and an upper limit of $R < 2.1$ was reported at the 90% C.L. [24] (using the information from Ref. 24, we can get $R = \frac{\mathcal{B}(X(3872) \rightarrow \gamma\psi(2S))}{\mathcal{B}(X(3872) \rightarrow \gamma J/\psi)} = 0.6 \pm 1.4$ as a good estimation of the central value and uncertainty). Although not in disagreement, BaBar and Belle results do show some tension on the decay rate of $X(3872) \rightarrow \gamma\psi(2S)$.

In a recent study at the LHCb experiment, strong evidence for the decay $X(3872) \rightarrow \gamma\psi(2S)$ was reported together with a measurement of R [16]. The analysis is based on a data sample of 1 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$ and 2 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$.

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In the full data sample, $591 \pm 48 B^\pm \rightarrow X(3872)K^\pm$, with $X(3872) \rightarrow \gamma J/\psi$, and $36.4 \pm 9.0 B^\pm \rightarrow X(3872)K^\pm$, with $X(3872) \rightarrow \gamma\psi(2S)$ were observed. The significance of the $X(3872) \rightarrow \gamma\psi(2S)$ signal is determined by simulating a large number of background-only toy MC experiments, taking into account all the uncertainties in the shape of the background distribution. The probability for the background to fluctuate to at least the number of observed events is found to be 1.2×10^{-5} , corresponding to a significance of 4.4σ .

LHCb measures

$$R = \frac{\mathcal{B}(X(3872) \rightarrow \gamma\psi(2S))}{\mathcal{B}(X(3872) \rightarrow \gamma J/\psi)} = 2.46 \pm 0.64 \pm 0.29.$$

This result is compatible with, but more precise than the BaBar and Belle measurements [15, 24].

As the measurements of all the above three experiments agree with each other, we can make a weighted average to give the best estimation of R . Neglecting the small correlated errors in the measurements, we obtain

$$\overline{R} = \frac{\mathcal{B}(X(3872) \rightarrow \gamma\psi(2S))}{\mathcal{B}(X(3872) \rightarrow \gamma J/\psi)} = 2.31 \pm 0.57.$$

This value does not support a pure $\bar{D}^0 D^{*0}$ molecular interpretation of the $X(3872)$ state, but agrees with expectations if the $X(3872)$ is a pure charmonium or a mixture of a molecule and a charmonium [3, 16]. Of course many of the calculations have model-dependent parameters, adjustment of the parameters may still reproduce the experimental data.

3. More information on the Y states

The study of charmonium states via ISR at the B -factories has proven to be very fruitful. In the process $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi$, the BaBar experiment observed the $Y(4260)$ [36]. This structure was also observed by the CLEO [37] and Belle experiments [38] with the same technique; moreover, there is a broad structure near 4.008 GeV in the Belle data. In an analysis of the $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-\psi(2S)$ process, BaBar found a structure at around 4.32 GeV [39], while the Belle observed two resonant structures at 4.36 GeV and 4.66 GeV [40]. Recently, BaBar updated $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-\psi(2S)$ analysis with the full data sample, and confirmed the $Y(4360)$ and $Y(4660)$ states [41]; and the update with the full Belle data samples further improve the measurements on the resonant structures [42]. The update of the $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi$ from both the BaBar and Belle experiments still show differences at the $Y(4008)$ mass region [32, 43].

BESIII experiment reported the cross section of $e^+e^- \rightarrow \pi^+\pi^-h_c$ final state with 13 energy points between 3.81 and 4.42 GeV [28], together with the CLEO-c measurement at 4.17 GeV [44], the data indicate the existence of a narrow structure at around 4.22 GeV and a wide structure at 4.29 GeV [45].

3.1. Confirmation of the $Y(4660)$

The BaBar experiment reported the update of the study of the process $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ with ISR events [41] with the full data sample. The data were recorded with the BaBar detector at CM energies at and near the $\Upsilon(nS)$ ($n = 2, 3, 4$) resonances and correspond to an integrated luminosity of 520 fb^{-1} . The $\psi(2S)$ is reconstructed with its decays into either $\pi^+\pi^-J/\psi$ or $\mu^+\mu^-$. They investigate the $\pi^+\pi^-\psi(2S)$ mass distribution from 3.95 to 5.95 GeV, and measure the CM energy dependence of the associated $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ cross section. The mass distribution exhibits evidence for two resonant structures. A fit to the $\pi^+\pi^-\psi(2S)$ mass distribution corresponding to the decay mode $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$ yields a mass value of $(4340 \pm 16 \pm 9) \text{ MeV}/c^2$ and a width of $(94 \pm 32 \pm 13) \text{ MeV}$ for the $Y(4360)$, and for the $Y(4660)$ a mass value of $(4669 \pm 21 \pm 3) \text{ MeV}/c^2$ and a width of $(104 \pm 48 \pm 10) \text{ MeV}$ [41]. The results are in good agreement with the Belle measurement [40] and confirm the $Y(4660)$ observed by the Belle experiment.

Using the 980 fb^{-1} full data sample taken with the Belle detector, Belle also updated the analysis with two $\psi(2S)$ decay modes [42], namely, $\pi^+\pi^-J/\psi$ and $\mu^+\mu^-$.

Fitting the mass spectrum of $\pi^+\pi^-\psi(2S)$ with two coherent BW functions (see Fig. 3), Belle obtains $M[Y(4360)] = (4346 \pm 6 \pm 2) \text{ MeV}/c^2$, $\Gamma[Y(4360)] = (111 \pm 10 \pm 7) \text{ MeV}$, $M[Y(4660)] = (4644 \pm 12 \pm 8) \text{ MeV}/c^2$ and $\Gamma[Y(4660)] = (59 \pm 12 \pm 2) \text{ MeV}$. There are two solutions from the fit. One solution has $\mathcal{B}[Y(4360) \rightarrow \pi^+\pi^-\psi(2S)] \cdot \Gamma_{e^+e^-}^{Y(4360)} = (10.6 \pm 0.6 \pm 0.7) \text{ eV}$ and $\mathcal{B}[Y(4660) \rightarrow \pi^+\pi^-\psi(2S)] \cdot \Gamma_{e^+e^-}^{Y(4660)} = (6.8 \pm 1.6 \pm 0.7) \text{ eV}$, while the other $\mathcal{B}[Y(4360) \rightarrow \pi^+\pi^-\psi(2S)] \cdot \Gamma_{e^+e^-}^{Y(4360)} = (9.2 \pm 0.8 \pm 0.7) \text{ eV}$ and $\mathcal{B}[Y(4660) \rightarrow \pi^+\pi^-\psi(2S)] \cdot \Gamma_{e^+e^-}^{Y(4660)} = (1.8 \pm 0.3 \pm 0.1) \text{ eV}$.

Since there are some events accumulating at the mass region of $Y(4260)$, the fit with the $Y(4260)$ included is also performed. In the fit, the mass and width of the $Y(4260)$ are fixed to the latest measured values at Belle [32]. There are four solutions with equally good fit quality. The signal significance of the $Y(4260)$ is estimated to be 2.1σ . The fit results are shown in Fig. 4 for one of the solutions. In this fit, one obtains $M[Y(4360)] = (4363 \pm 8) \text{ MeV}/c^2$, $\Gamma[Y(4360)] = (80 \pm 16) \text{ MeV}$, $M[Y(4660)] = (4657 \pm 9) \text{ MeV}/c^2$, and $\Gamma[Y(4660)] = (68 \pm 11) \text{ MeV}$. Here the errors are statistical only.

The cross section for $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ in each $\pi^+\pi^-\psi(2S)$ mass bin is calculated and the results in the full solid angle are shown in Fig. 5, where the error bars include the statistical uncertainties in the signal and the background subtraction. The systematic error for the cross section measurement is 4.8% and common to all the data points.

Possible charged charmoniumlike structures in $\pi^\pm\psi(2S)$ final states from the $Y(4360)$ or $Y(4660)$ decays are searched for with the selected candidate events at Belle. Figure 6 shows the sum of $M_{\pi^-\psi(2S)}$ and $M_{\pi^+\psi(2S)}$ distributions in $Y(4360)$ decays from both the $\pi^+\pi^-J/\psi$ and the $\mu^+\mu^-$ modes. There is a bump at $4.05 \text{ GeV}/c^2$ in the $\pi^\pm\psi(2S)$ invariant mass distribution, which could be the

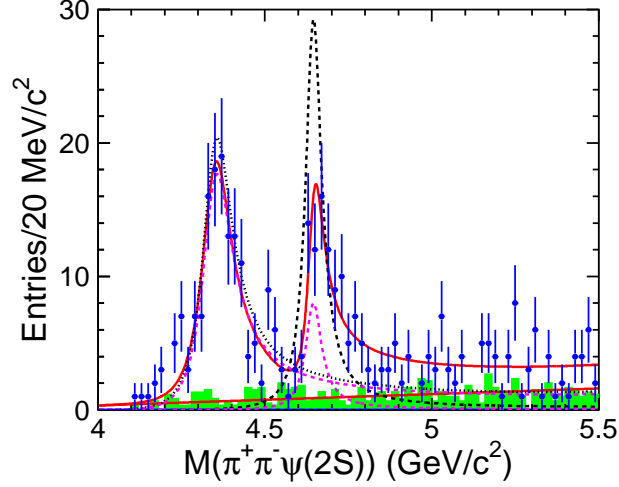


Fig. 3. The $\pi^+\pi^-\psi(2S)$ invariant mass distribution from the Belle experiment and the fit results with the coherent sum of two BW functions. The sum of $\pi^+\pi^-J/\psi$ and $\mu^+\mu^-$ modes is shown. The points with error bars are data while the shaded histograms the normalized $\psi(2S)$ sideband backgrounds. The curves show the best fit and the dashed curves, which are from the two solutions, show the contributions from different BW components. The interference between the two resonances is not shown.

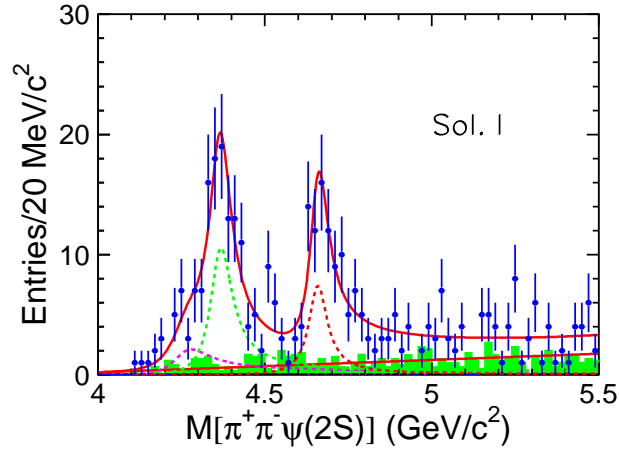


Fig. 4. Same as Fig. 3 but fit with the coherent sum of three BW functions.

$Z_c(4020)$ [28] or the $Z_c(4025)$ [59]. A simple fit with a BW function for the bump and a MC simulated three-body phase space for the non-resonant background yields a mass of $(4040 \pm 9) \text{ MeV}/c^2$ and a width of $(26 \pm 18) \text{ MeV}$. Here the errors are statistical only. The statistical significance of the signal is 2.2σ . Since each event is counted twice, the significance is a bit overestimated. The same distribution in $Y(4660)$ decays is also checked. The $Y(4660)$ sample is very limited in statistics, and there is no significant structures in the $\pi^\pm\psi(2S)$ system.

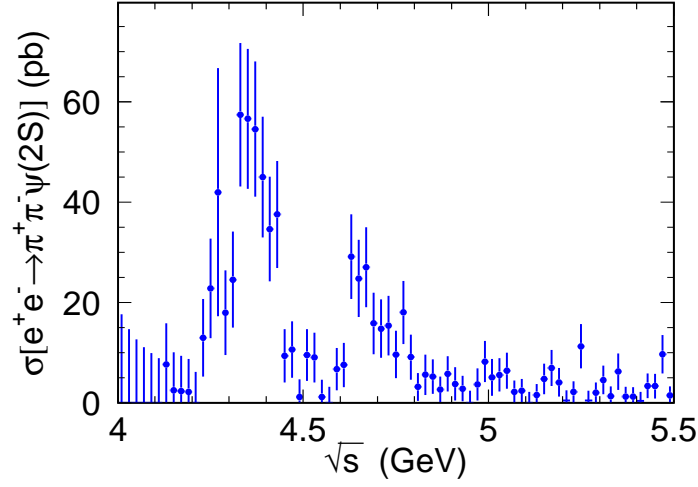


Fig. 5. The measured $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ cross section for $\sqrt{s}=4.0$ to 5.5 GeV from the Belle experiment. The errors are the summed statistical errors of the numbers of signal and background events. A common systematic error of 4.8% for all the data points is not shown.

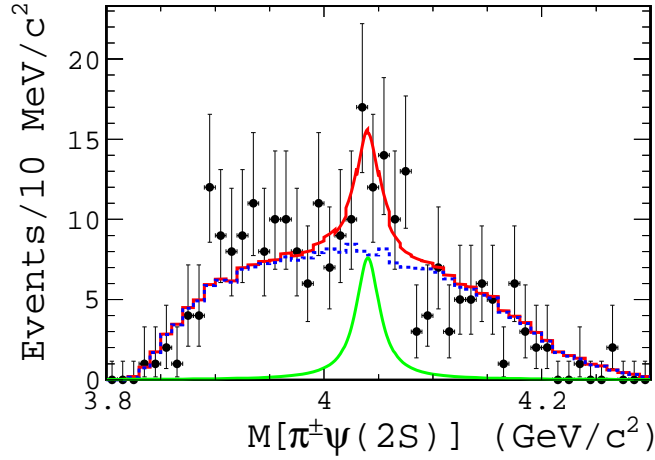


Fig. 6. The distribution of $M_{\pi^\pm\psi(2S)}$ from the sum of the $\pi^+\pi^-J/\psi$ and the $\mu^+\mu^-$ modes for $Y(4360)$ events observed in Belle data. The curve shows the best fit. This blank histogram is the MC simulation of three-body phase space.

3.2. Measurement of $e^+e^- \rightarrow \pi^+\pi^-h_c$

BESIII studied $e^+e^- \rightarrow \pi^+\pi^-h_c$ at 13 CM energies from 3.900 to 4.420 GeV [28]. In the studies, the h_c is reconstructed via its electric-dipole (E1) transition $h_c \rightarrow$

$\gamma\eta_c$ with $\eta_c \rightarrow X_i$, where X_i signifies 16 exclusive hadronic final states: $p\bar{p}$, $2(\pi^+\pi^-)$, $2(K^+K^-)$, $K^+K^-\pi^+\pi^-$, $p\bar{p}\pi^+\pi^-$, $3(\pi^+\pi^-)$, $K^+K^-2(\pi^+\pi^-)$, $K_S^0K^\pm\pi^\mp$, $K_S^0K^\pm\pi^\mp\pi^\pm\pi^\mp$, $K^+K^-\pi^0$, $p\bar{p}\pi^0$, $\pi^+\pi^-\eta$, $K^+K^-\eta$, $2(\pi^+\pi^-)\eta$, $\pi^+\pi^-\pi^0\pi^0$, and $2(\pi^+\pi^-)\pi^0\pi^0$.

The cross sections are listed in Table 3 and shown in Fig. 7. The CLEO-c experiment did a similar analysis, but with significant signal only at CM energy 4.17 GeV [44], the result is $\sigma = (15.6 \pm 2.3 \pm 1.9 \pm 3.0)$ pb, where the third error is from the uncertainty in $\mathcal{B}[\psi(2S) \rightarrow \pi^0 h_c]$.

Table 3. $e^+e^- \rightarrow \pi^+\pi^-h_c$ cross sections measured from the BESIII experiment. For the first three energy points, besides the upper limits, the central values and the statistical errors which will be used in the fits below are also listed. The second errors are systematic errors and the third ones are from the uncertainty in $\mathcal{B}(h_c \rightarrow \gamma\eta_c)$.

\sqrt{s} (GeV)	$\sigma(e^+e^- \rightarrow \pi^+\pi^-h_c)$ (pb)
3.900	0.0 ± 6.0 or < 8.3
4.009	1.9 ± 1.9 or < 5.0
4.090	0.0 ± 7.4 or < 13
4.190	$17.7 \pm 9.8 \pm 1.6 \pm 2.8$
4.210	$34.8 \pm 9.5 \pm 3.2 \pm 5.5$
4.220	$41.9 \pm 10.7 \pm 3.8 \pm 6.6$
4.230	$50.2 \pm 2.7 \pm 4.6 \pm 7.9$
4.245	$32.7 \pm 10.3 \pm 3.0 \pm 5.1$
4.260	$41.0 \pm 2.8 \pm 3.7 \pm 6.4$
4.310	$61.9 \pm 12.9 \pm 5.6 \pm 9.7$
4.360	$52.3 \pm 3.7 \pm 4.8 \pm 8.2$
4.390	$41.8 \pm 10.8 \pm 3.8 \pm 6.6$
4.420	$49.4 \pm 12.4 \pm 4.5 \pm 7.6$

The cross sections are of the same order of magnitude as those of the $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ measured by previous experiments [31, 32, 43], but with a different line shape (see Fig. 7). There is a broad structure at high energy with a possible local maximum at around 4.23 GeV. The BESIII and the CLEO-c measurements are used to extract the resonant structures in $e^+e^- \rightarrow \pi^+\pi^-h_c$ in Ref. 45.

As the systematic error ($\pm 18.1\%$) of the BESIII experiment is common for all the data points, only the statistical errors are used in the fits. The CLEO-c measurement is independent from the BESIII experiment, and all the errors added in quadrature (± 4.2 pb) is taken as the total error and is used in the fits. A least χ^2 fit method with [46]

$$\chi^2 = \sum_{i=1}^{14} \frac{(\sigma_i^{\text{meas}} - \sigma^{\text{fit}}(m_i))^2}{(\Delta\sigma_i^{\text{meas}})^2}$$

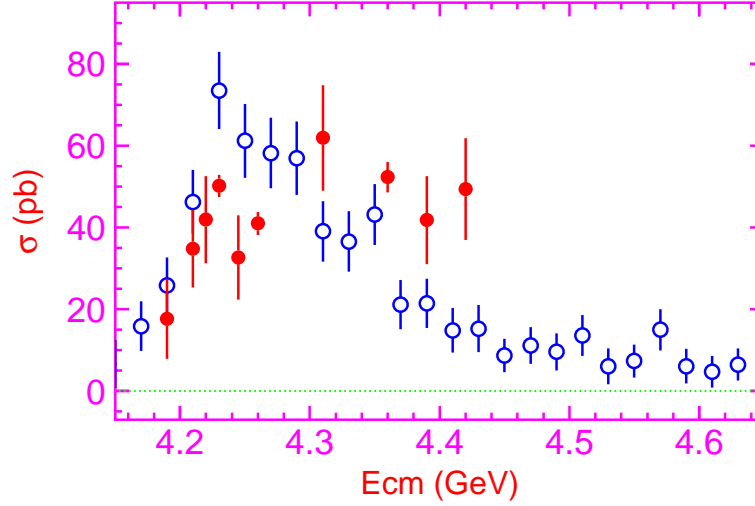


Fig. 7. The comparison between the cross sections of $e^+e^- \rightarrow \pi^+\pi^-h_c$ from BESIII (dots with error bars) and those of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ from Belle (open circles with error bars). The errors are statistical only.

is used, where $\sigma_i^{\text{meas}} \pm \Delta\sigma_i^{\text{meas}}$ is the experimental measurement, and $\sigma^{\text{fit}}(m_i)$ is the cross section calculated from the model below with the parameters from the fit. Here m_i is the energy corresponds to the i th energy point.

As the line shape above 4.42 GeV is unknown, it is not clear whether the large cross section at high energy will decrease or not. The data are fitted with two different scenarios.

Assuming the cross section follows the three-body phase space and there is a narrow resonance at around 4.2 GeV, the cross sections are fitted with the coherent sum of two amplitudes, a constant and a constant-width relativistic BW function, i.e.,

$$\sigma(m) = |\text{const} \cdot \sqrt{\rho(m)} + e^{i\phi} BW(m) \sqrt{\rho(m)/\rho(M)}|^2,$$

where $\rho(m)$ is the 3-body phase space factor, $BW(m) = \frac{\sqrt{12\pi\Gamma_{e^+e^-}\mathcal{B}(\pi^+\pi^-h_c)\Gamma_{\text{tot}}}}{m^2 - M^2 + iM\Gamma_{\text{tot}}}$, is the BW function for a vector state, with mass M , width Γ_{tot} , electron partial width $\Gamma_{e^+e^-}$, and the branching fraction to $\pi^+\pi^-h_c$, $\mathcal{B}(\pi^+\pi^-h_c)$, keep in mind that from the fit one can only extract the product $\Gamma_{e^+e^-}\mathcal{B}(\pi^+\pi^-h_c)$. The constant term const and the relative phase, ϕ , between the two amplitudes are also free parameters in the fit together with the resonant parameters of the BW function.

The fit indicates the existence of a resonance (called $Y(4220)$ hereafter) with a mass of $(4216 \pm 7) \text{ MeV}/c^2$ and width of $(39 \pm 17) \text{ MeV}$, and the goodness-of-the-fit is $\chi^2/\text{ndf} = 11/9$, corresponding to a confidence level of 27%. There are two solutions for the $\Gamma_{e^+e^-} \times \mathcal{B}(Y(4220) \rightarrow \pi^+\pi^-h_c)$ which are $(3.2 \pm 1.5) \text{ eV}$ and $(6.0 \pm 2.4) \text{ eV}$. Here all the errors are from fit only. Fitting the cross sections without the $Y(4220)$ results in a very bad fit, $\chi^2/\text{ndf} = 73/13$, corresponding to a confidence

level of 2.5×10^{-10} . The statistical significance of the $Y(4220)$ is calculated to be 7.1σ comparing the two χ^2 s obtained above and taking into account the change of the number-of-degrees-of-freedom. Figure 8 (top panel) shows the final fit with the $Y(4220)$.

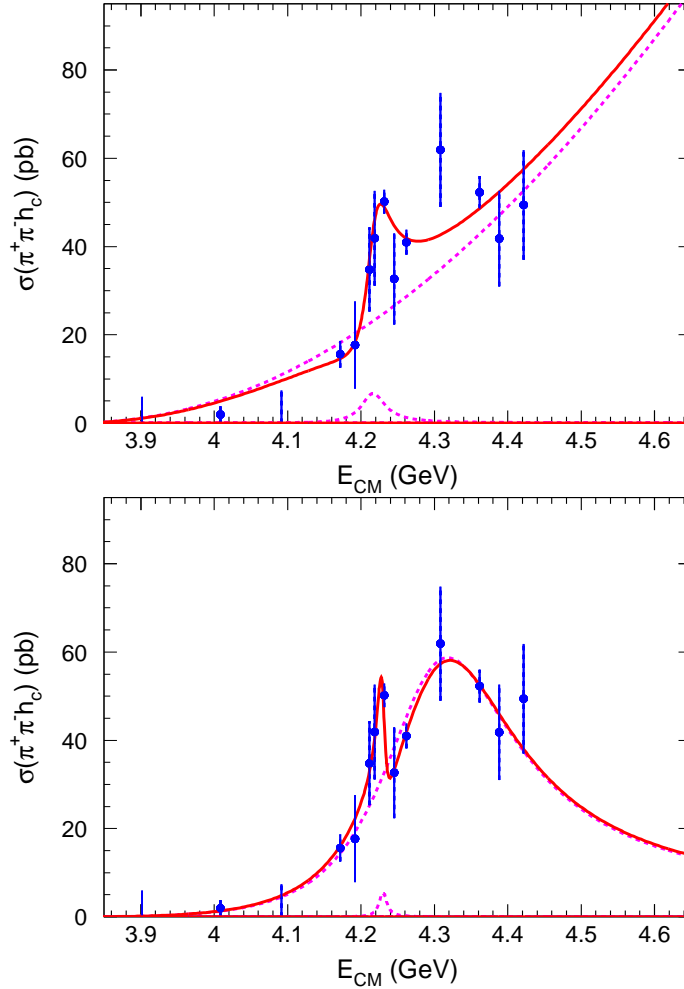


Fig. 8. The fit to the cross sections of $e^+e^- \rightarrow \pi^+\pi^-h_c$ from BESIII and CLEO-c (dots with error bars). Solid curves show the best fits, and the dashed ones are individual component. Top panel is the fit with the coherent sum of a phase space amplitude and a BW function, and the bottom panel is the coherent sum of two BW functions.

Assuming the cross section decreases at high energy, the cross sections are fitted with the coherent sum of two constant-width relativistic BW functions, i.e.,

$$\sigma(m) = |BW_1(m) \cdot \sqrt{\rho(m)/\rho(M_1)} + e^{i\phi} BW_2(m) \cdot \sqrt{\rho(m)/\rho(M_2)}|^2,$$

where both BW_1 and BW_2 take the same form as $BW(m)$ above but with different resonant parameters.

The fit indicates the existence of the $Y(4220)$ with a mass of (4230 ± 10) MeV/ c^2 and width of (12 ± 36) MeV, as well as a broad resonance, the $Y(4290)$, with a mass of (4293 ± 9) MeV/ c^2 and width of (222 ± 67) MeV. The goodness-of-the-fit is $\chi^2/\text{ndf} = 2/7$, corresponding to a confidence level of 97%, an almost perfect fit. There are two solutions for the $\Gamma_{e^+e^-} \times \mathcal{B}[Y(4220)/Y(4290) \rightarrow \pi^+\pi^-h_c]$ which are (0.07 ± 0.07) eV/ (16.1 ± 2.2) eV and (2.7 ± 4.9) eV/ (19.0 ± 5.9) eV. Again, here the errors are from fit only. Fitting the cross sections without the $Y(4220)$ results in a much worse fit, $\chi^2/\text{ndf} = 31/11$, corresponding to a confidence level of 1.3×10^{-3} . The statistical significance of the $Y(4220)$ is calculated to be 4.5σ comparing the two χ^2 s obtained above and taking into account the change of the number-of-degrees-of-freedom. Figure 8 (bottom panel) shows the final fit with the $Y(4220)$ and $Y(4290)$.

From the two fits showed above, we conclude that very likely there is a narrow structure at around 4.22 GeV/ c^2 , although we are not sure if there is a broad resonance at 4.29 GeV/ c^2 . We try to average the results from the fits to give the best estimation of the resonant parameters. For the $Y(4220)$, we obtain

$$\begin{aligned} M(Y(4220)) &= (4216 \pm 18) \text{ MeV}/c^2, \\ \Gamma_{\text{tot}}(Y(4220)) &= (39 \pm 32) \text{ MeV}, \\ \Gamma_{e^+e^-}^{Y(4220)} \times \mathcal{B}[Y(4220) \rightarrow \pi^+\pi^-h_c] &= (4.6 \pm 4.6) \text{ eV}. \end{aligned}$$

While for the $Y(4290)$, we obtain

$$\begin{aligned} M(Y(4290)) &= (4293 \pm 9) \text{ MeV}/c^2, \\ \Gamma_{\text{tot}}(Y(4290)) &= (222 \pm 67) \text{ MeV}, \\ \Gamma_{e^+e^-}^{Y(4290)} \times \mathcal{B}[Y(4290) \rightarrow \pi^+\pi^-h_c] &= (18 \pm 8) \text{ eV}. \end{aligned}$$

Here the errors include both statistical and systematic errors. The results from the two solutions and the two fit scenarios are covered by enlarged errors, the common systematic error in the cross section measurement is included in the error of the $\Gamma_{e^+e^-}$.

It is noticed that the uncertainties of the resonant parameters of the $Y(4220)$ are large, this is due to (1) the lack of data at CM energies above 4.42 GeV which may discriminate which of the two above scenarios is correct, and (2) the lack of high precision measurements around the $Y(4220)$ peak, especially between 4.23 and 4.26 GeV. The two-fold ambiguity in the fits is a nature consequence of the coherent sum of two amplitudes [47], although high precision data will not resolve the problem, they will reduce the errors in $\Gamma_{e^+e^-}$ from the above fits. As the fit with a phase space amplitude predicts rapidly increasing cross section at high energy, it is very unlikely to be true, so the results from the fit with two resonances is more likely to be true. More measurements from the BESIII experiments at CM energies

above 4.42 GeV and more precise data at around the $Y(4220)$ peak will also be crucial to settle down all these problems.

There are thresholds of $D\bar{D}_1$ [48], $\omega\chi_{cJ}$ [49, 50], $D_s^{*+}D_s^{*-}$ [30] at the $Y(4220)$ mass region, these make the identification of the nature of this structure very complicated. The fits described in this paper supply only one possibility of interpreting the data. In Ref. 51, the BESIII measurements [28] were described with the presence of one relative S -wave $D\bar{D}_1 + c.c.$ molecular state $Y(4260)$ and a non-resonant background term; while in Ref. 52, the BESIII data [28] were fitted with a model where the $Y(4260)$ and $Y(4360)$ are interpreted as the mixture of two hadroncharmonium states. It is worth to point out that various QCD calculations indicate that the charmonium-hybrid lies in the mass region of these two Y states [53] and the $c\bar{c}$ tend to be in a spin-singlet state. Such a state may couple to a spin-singlet charmonium state such as h_c strongly, this makes the $Y(4220)$ and/or $Y(4290)$ good candidates for the charmonium-hybrid states.

4. Observation of charged charmoniumlike states

Searching for the charged charmoniumlike state is the most promising way of studying the exotic hadrons, since such a state must contain at least four quarks and thus could not be a conventional meson.

The Belle collaboration first reported evidence for a narrow $Z(4430)^-$ peak, with mass $M = (4433 \pm 4 \pm 2) \text{ MeV}/c^2$ and width $\Gamma = 45_{-13}^{+18+30} \text{ MeV}$, in the $\pi^-\psi(2S)$ invariant mass distribution in $B \rightarrow K\pi^-\psi(2S)$ decays [54], and very soon reported another two exotic $\pi^-\chi_{c1,2}$ structures in $B \rightarrow K\pi^-\chi_{c1}$ decays [55] at masses 4050 and 4250 MeV/c^2 . The BaBar collaboration did the same analyses [56, 57], but did not confirm the existence of these structures. On the other hand, the BaBar's results did not contradict the Belle evidence for these states due to low statistics. This has been an open question for a very long time since there were no new data available until very recently.

In the study of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ at CM energies around 4.26 GeV, the BESIII [31] and Belle [32] experiments observed a charged charmoniumlike state, the $Z_c(3900)$ in its $\pi J/\psi$ decays, which was confirmed shortly after with CLEO data at a CM energy of 4.17 GeV [33]. More recently, BESIII observed a charged $Z_c(3885)$ state in $e^+e^- \rightarrow \pi^\pm(D\bar{D}^*)^\mp$ [58], a charged $Z_c(4025)$ state in $e^+e^- \rightarrow \pi^\pm(D^*\bar{D}^*)^\mp$ [59], and a charged $Z_c(4020)$ state in $e^+e^- \rightarrow \pi^\pm(\pi^\mp h_c)$ [28]. These states seem to indicate that a new class of hadrons has been observed.

To take into account the interference effect between the $Z(4430)^-$ and the K^* intermediate states in $B \rightarrow K\pi^-\psi(2S)$ decays, the Belle collaboration updated their $Z(4430)^-$ results with a four-dimensional (4D) amplitude analysis [60]. The $Z(4430)^-$ is observed with a significance of 5.2σ , a much larger mass of $M[Z(4430)^-] = (4485 \pm 22_{-11}^{+28}) \text{ MeV}/c^2$, and a large width of $\Gamma[Z(4430)^-] = (200_{-46-35}^{+41+26}) \text{ MeV}$. The product branching fractions are measured to be $\mathcal{B}(B^0 \rightarrow Z(4430)^-K^+) \times \mathcal{B}(Z(4430)^- \rightarrow \pi^-\psi(2S)) = (6.0_{-2.0-1.4}^{+1.7+2.5}) \times 10^{-5}$, and spin-parity

$J^P = 1^+$ is favored over the other assignments by more than 3.4σ . This was confirmed recently by the LHCb experiment in a 4D model-dependent amplitude fit to a sample of $25176 \pm 174 B^0 \rightarrow K^+ \pi^- \psi(2S)$, $\psi(2S) \rightarrow \mu^+ \mu^-$ events [17].

Belle observed a $Z(4200)^-$ with more than 7.2σ significance and the evidence for the $Z(4430)^-$ in the $\pi^\pm J/\psi$ invariant mass distribution in $B \rightarrow K \pi^- J/\psi$ decays [61].

As there are at least four quarks within the all these Z_c^- states, they have been interpreted either as tetraquark states with a pair of charm-anticharm quarks and a pair of light quarks, molecular states of two charmed mesons ($\bar{D}D^*$, \bar{D}^*D^* , $\bar{D}D_1$, \bar{D}^*D_1 , etc.), hadro-quarkonium states, or other configurations.

4.1. Observation of the $Z_c(3900)$ and $Z_c(3885)$

BESIII experiment studied the process $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at a CM energy of 4.260 GeV using a 525 pb^{-1} data sample [31]. A structure at around $3.9 \text{ GeV}/c^2$ is observed in the $\pi^\pm J/\psi$ mass spectrum with a statistical significance larger than 8σ , which is referred to as the $Z_c(3900)$. A fit to the $\pi^\pm J/\psi$ invariant mass spectrum (see Fig. 9), neglecting interference, results in a mass of $(3899.0 \pm 3.6 \pm 4.9) \text{ MeV}/c^2$ and a width of $(46 \pm 10 \pm 20) \text{ MeV}$. Its production ratio is measured to be $R = \frac{\sigma(e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} = (21.5 \pm 3.3 \pm 7.5)\%$.

At Belle experiment, the cross section of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ is measured from 3.8 GeV to 5.5 GeV using ISR method. The $Y(4260)$ resonance is observed and its resonant parameters are determined. The intermediate states in $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ decays are also investigated [32]. The $Z_c(3900)$ (was named $Z(3900)^+$ in the Belle paper) state with a mass of $(3894.5 \pm 6.6 \pm 4.5) \text{ MeV}/c^2$ and a width of $(63 \pm 24 \pm 26) \text{ MeV}$ is observed in the $\pi^\pm J/\psi$ mass spectrum (see Fig. 9) with a statistical significance larger than 5.2σ .

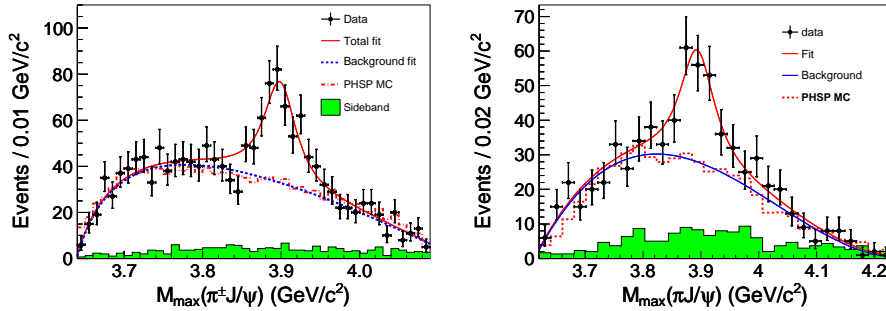


Fig. 9. Unbinned maximum likelihood fit to the distribution of the $M_{\max}(\pi J/\psi)$ (left panel from BESIII and right panel from Belle). Points with error bars are data, the curves are the best fit, the dashed histograms are the phase space distributions and the shaded histograms are the non- $\pi^+\pi^- J/\psi$ background estimated from the normalized J/ψ sidebands.

The $Z_c(3900)$ was confirmed shortly after with CLEO-c data at a CM energy of 4.17 GeV [33], the mass and width agree with the BESIII and Belle measurements very well.

This state is close to and above the $D\bar{D}^*$ mass threshold. With the same data sample at $\sqrt{s} = 4.26$ GeV, BESIII experiment reported on a study of the process $e^+e^- \rightarrow \pi^\pm(D\bar{D}^*)^\mp$. A structure (referred to as $Z_c(3885)$) is observed in the $(D\bar{D}^*)^\mp$ invariant mass distribution [58]. When fitted to a mass-dependent-width BW function, the pole mass and width are determined to be $(3883.9 \pm 1.5 \pm 4.2)$ MeV/ c^2 and $(24.8 \pm 3.3 \pm 11.0)$ MeV, respectively (see Fig. 10). The angular distribution of the $Z_c(3885)$ system favors a $J^P = 1^+$ assignment for the structure and disfavors 1^- or 0^- . The production rate is measured to be $\sigma(e^+e^- \rightarrow \pi^\pm Z_c(3885)^\mp) \times \mathcal{B}(Z_c(3885)^\mp \rightarrow (D\bar{D}^*)^\mp) = (83.5 \pm 6.6 \pm 22.0)$ pb.

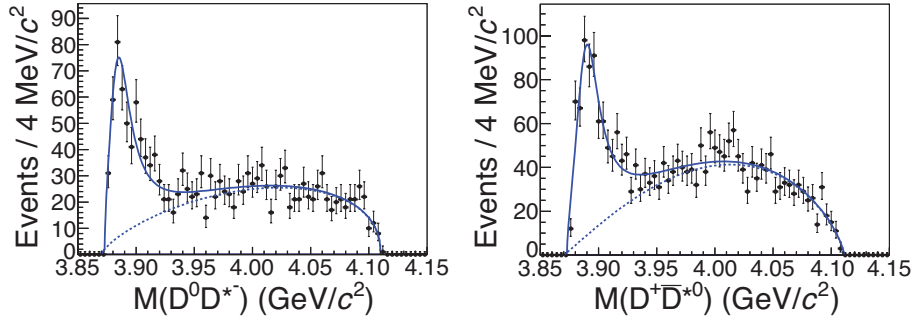


Fig. 10. The $M(D^0 D^{*-})$ (left) and $M(D^+ \bar{D}^{*0})$ (right) distributions for selected events at $\sqrt{s} = 4.26$ GeV. The curves show the best fits.

An important question is whether or not the $Z_c(3885)$ is the same as the $Z_c(3900)$. The mass and width of the $Z_c(3885)$ are 2σ and 1σ , respectively, below those of the $Z_c(3900)$ observed by BESIII and Belle. However neither fit considers the possibility of interference with a coherent non-resonant background that could shift the results. A J^P quantum number determination of the $Z_c(3900)$ would provide an additional test of this possibility.

Assuming the $Z_c(3885)$ structure is due to the $Z_c(3900)$, one obtains $\frac{\Gamma(Z_c(3885) \rightarrow D\bar{D}^*)}{\Gamma(Z_c(3900) \rightarrow \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$. This ratio is much smaller than typical values for decays of conventional charmonium states above the open charm threshold. For example: $\Gamma(\psi(3770) \rightarrow D\bar{D})/\Gamma(\psi(3770) \rightarrow \pi^+\pi^- J/\psi) = 482 \pm 84$ [30] and $\Gamma(\psi(4040) \rightarrow D^{(*)}\bar{D}^{(*)})/\Gamma(\psi(4040) \rightarrow \eta J/\psi) = 192 \pm 27$ [62]. This suggests the influence of very different dynamics in the $Y(4260)$ - $Z_c(3900)$ system.

Assuming that the $Z_c(3885)$ and $Z_c(3900)$ are the same structure and neglecting the slightly different parametrization of the resonances, a weighted average of the above four measurements yields the best estimation of the resonant parameters of the $Z_c(3900)$, i.e., $M_{Z_c(3900)} = (3888.6 \pm 2.7)$ MeV/ c^2 and $\Gamma_{Z_c(3900)} = (34.7 \pm$

6.6) MeV.

4.2. Observation of the $Z_c(4020)$ and $Z_c(4025)$

BESIII measured $e^+e^- \rightarrow \pi^+\pi^-h_c$ cross sections [28] at CM energies between 3.90 and 4.42 GeV as described in Sec. 3.2.

Intermediate states are studied by examining the Dalitz plot of the selected $\pi^+\pi^-h_c$ candidate events. The h_c signal is selected using $3.518 < M_{\gamma\eta_c} < 3.538$ GeV/ c^2 , $\pi^+\pi^-h_c$ samples of 859 events at 4.23 GeV, 586 events at 4.26 GeV, and 469 events at 4.36 GeV are obtained with purities of 65%. While there are no clear structures in the $\pi^+\pi^-$ system, there is clear evidence for an exotic charmonium-like structure in the $\pi^\pm h_c$ system as clearly shown in the Dalitz plot. Figure 11 shows the projection of the $M(\pi^\pm h_c)$ (two entries per event) distribution for the signal events, as well as the background events estimated from normalized h_c mass sidebands. There is a significant peak at around 4.02 GeV/ c^2 (the $Z_c(4020)$), and there are also some events at around 3.9 GeV/ c^2 (inset of Fig. 11), which could be the $Z_c(3900)$. The individual data sets at 4.23 GeV, 4.26 GeV and 4.36 GeV show similar structures.

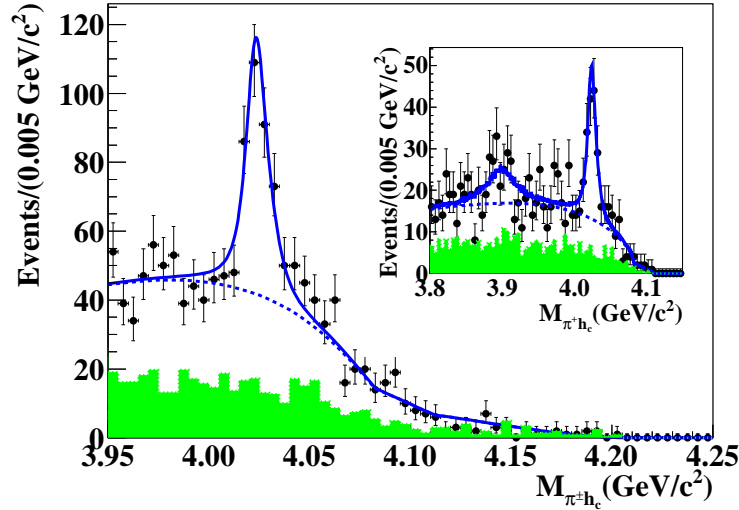


Fig. 11. Sum of the simultaneous fits to the $M(\pi^\pm h_c)$ distributions at 4.23 GeV, 4.26 GeV, and 4.36 GeV in the BESIII data; the inset shows the sum of the simultaneous fit to the $M_{\pi^+h_c}$ distributions at 4.23 GeV and 4.26 GeV with $Z_c(3900)$ and $Z_c(4020)$. Dots with error bars are data; shaded histograms are normalized sideband background; the solid curves show the total fit, and the dotted curves the backgrounds from the fit.

An unbinned maximum likelihood fit is applied to the $M(\pi^\pm h_c)$ distribution summed over the 16 η_c decay modes. The data at 4.23 GeV, 4.26 GeV, and 4.36 GeV

are fitted simultaneously with the same signal function with common mass and width. Figure 11 shows the fit results. The mass of the $Z_c(4020)$ is measured to be $(4022.9 \pm 0.8 \pm 2.7) \text{ MeV}/c^2$, and the width is $(7.9 \pm 2.7 \pm 2.6) \text{ MeV}$. The statistical significance of the $Z_c(4020)$ signal is calculated by comparing the fit likelihoods with and without the signal. Besides the nominal fit, the fit is also performed by changing the fit range, the signal shape, or the background shape. In all cases, the significance is found to be greater than 8.9σ .

Adding a $Z_c(3900)$ with mass and width fixed to the BESIII measurement [31] in the fit, results in a statistical significance of 2.1σ (see the inset of Fig. 11). The upper limits on the production cross sections are set as $\sigma(e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^-h_c) < 13 \text{ pb}$ at 4.23 GeV and $< 11 \text{ pb}$ at 4.26 GeV, at the 90% confidence level (C.L.). This is lower than that of $Z_c(3900) \rightarrow \pi^\pm J/\psi$ [31].

BESIII experiment also studied the process $e^+e^- \rightarrow (D^*\bar{D}^*)^\pm \pi^\mp$ at a CM energy of 4.26 GeV using a 827 pb^{-1} data sample [59]. Based on a partial reconstruction technique, the Born cross section is measured to be $(137 \pm 9 \pm 15) \text{ pb}$. A structure near the $(D^*\bar{D}^*)^\pm$ threshold in the π^\mp recoil mass spectrum is observed, which is denoted as the $Z_c(4025)$ (see Fig. 12). The measured mass and width of the structure are $(4026.3 \pm 2.6 \pm 3.7) \text{ MeV}/c^2$ and $(24.8 \pm 5.6 \pm 7.7) \text{ MeV}$, respectively, from a fit with a constant-width BW function for the signal. Its production ratio $\frac{\sigma(e^+e^- \rightarrow Z_c^\pm(4025)\pi^\mp \rightarrow (D^*\bar{D}^*)^\pm \pi^\mp)}{\sigma(e^+e^- \rightarrow (D^*\bar{D}^*)^\pm \pi^\mp)}$ is determined to be $0.65 \pm 0.09 \pm 0.06$.

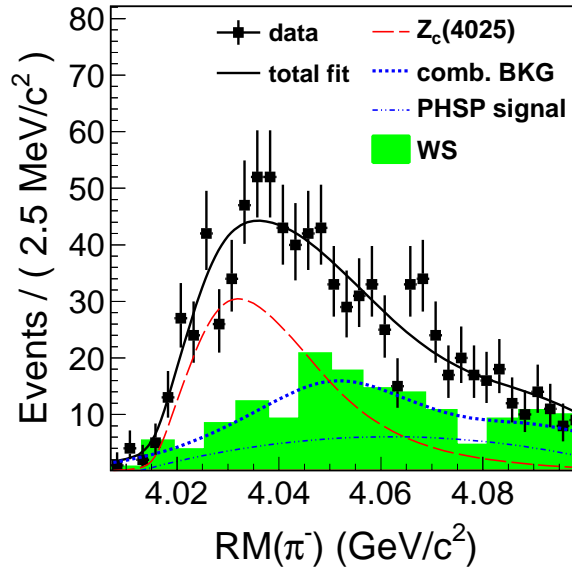


Fig. 12. Unbinned maximum likelihood fit to the π^\mp recoil mass spectrum in $e^+e^- \rightarrow (D^*\bar{D}^*)^\pm \pi^\mp$ at $\sqrt{s} = 4.26 \text{ GeV}$ at BESIII.

The $Z_c(4025)$ parameters agree within 1.5σ of those of the $Z_c(4020)$. Very prob-

ably they are the same state. As the results on the $Z_c(4025)$ is only from the data at 4.26 GeV, extending the analysis to the data at 4.23 GeV and 4.36 GeV will probably give us a definite answer.

4.3. Confirmation of the $Z(4430)^-$

Observed by the Belle collaboration [54] but not confirmed by the BaBar collaboration [56], the existence of the $Z(4430)^-$ has been questioned until very recently the LHCb experiment [17] reported a 4D model-dependent amplitude fit to a much larger sample of $B^0 \rightarrow K^+\pi^-\psi(2S)$ events. In this LHCb analysis, the $Z(4430)^-$ was observed at larger than 13.9σ level, and the spin-parity is determined to be 1^+ .

$25,176 \pm 174$ $B^0 \rightarrow \psi(2S)\pi^-K^+$, $\psi(2S) \rightarrow \mu^+\mu^-$ events are selected for the 4D amplitude analysis at LHCb [17]. The B^0 candidates are selected using particle identification information, transverse momentum thresholds and requiring separation of the tracks and of the B^0 vertex from the primary pp interaction points. The background fraction is determined from the B^0 candidate invariant mass distribution to be $(4.1 \pm 0.1)\%$. The background is dominated by combinations of $\psi(2S)$ from B decays with random kaons and pions.

The LHCb amplitude model includes all known $K^{*0} \rightarrow K^+\pi^-$ resonances with nominal mass within or slightly above the kinematic limit in $B^0 \rightarrow K^+\pi^-\psi(2S)$ decays: $K_0^*(800)$, $K_0^*(1430)$ for $J = 0$; $K^*(892)$, $K^*(1410)$ and $K^*(1680)$ for $J = 1$; $K_2^*(1430)$ for $J = 2$; and $K_3^*(1780)$ for $J = 3$. They also include a non-resonant $J = 0$ term in the fits.

The above model does not describe the data well, the confidence level of the fit is below 2×10^{-6} , equivalent to 4.8σ in the Gaussian distribution, according to toy MC simulation. By adding a $Z(4430)^-$ component with $J^P = 1^+$ in the $\pi\psi(2S)$ system to the amplitude, the C.L. of the fit improves to a few percent level, indicating a reasonable fit. The resonant parameters are found to be $M[Z(4430)^-] = (4475 \pm 7_{-25}^{+15})$ MeV/ c^2 , $\Gamma[Z(4430)^-] = (172 \pm 13_{-34}^{+37})$ MeV. The spin-parity is found to be 1^+ , the 0^- , 1^- , 2^+ and 2^- hypotheses are ruled out at very high significance level.

With the large statistics, LHCb experiment is able to divide the $M^2[\pi\psi(2S)]$ bins around the $Z(4430)^-$ peak and fit the real and imaginary parts of the $Z(4430)^-$ amplitudes. The resulting Argand diagram is consistent with a rapid change of the $Z(4430)^-$ phase when its magnitude reaches the maximum, a behavior characteristic of a resonance.

With the LHCb results, the first charged charmoniumlike state $Z(4430)^-$ is established after seven years of its discovery at Belle [60].

4.4. Observation of the $Z(4200)^-$

The Belle experiment analyzed $B^0 \rightarrow K^-\pi^+J/\psi$ with $J/\psi \rightarrow e^+e^-$ or MM with the full $\Upsilon(4S)$ data sample, corresponds to 711 fb^{-1} data with 772 million $B\bar{B}$ pairs [61]. About 30,000 signal events are selected and a 4D amplitude analysis is

performed with $K_0^*(800)$, $K_0^*(1430)$, and $K_0^*(1950)$ for $J = 0$; $K^*(892)$, $K^*(1410)$, and $K^*(1680)$ for $J = 1$; $K_2^*(1430)$ and $K_2^*(1980)$ for $J = 2$; $K_3^*(1780)$ for $J = 3$, and $K_4^*(2045)$ for $J = 4$ in the $K\pi$ system; and a $J^P = 1^+$ BW function in the $\pi J/\psi$ system.

A resonant (named $Z_c(4200)$) is needed to describe the data with a statistical significance of more than 7.2σ including the systematic effect. The resonant parameters are determined to be $M[Z(4200)^-] = (4196_{-29}^{+31+17})$ MeV/ c^2 , $\Gamma[Z(4200)^-] = (370_{-70}^{+70+70})$ MeV. The product branching fractions are measured to be

$$\mathcal{B}(B^0 \rightarrow Z(4200)^- K^+) \times \mathcal{B}(Z(4200)^- \rightarrow \pi^- J/\psi) = (2.2_{-0.5-0.6}^{+0.7+1.1}) \times 10^{-5}.$$

The spin-parity is found to be 1^+ , the 0^- , 1^- , 2^+ and 2^- hypotheses are ruled out at at least 5.6σ level.

In addition, a strong evidence for $Z(4430)^- \rightarrow \pi^- J/\psi$ is observed, with a significance level of more than 4.0σ . However, no significant $Z_c(3900)$ is observed. The product branching fractions are measured to be

$$\mathcal{B}(B^0 \rightarrow Z(4430)^- K^+) \times \mathcal{B}(Z(4430)^- \rightarrow \pi^- J/\psi) = (5.4_{-1.0-0.9}^{+4.0+1.1}) \times 10^{-6}.$$

Comparing with the measurement of $Z(4430)^- \rightarrow \pi^- \psi(2S)$ listed above, we found that $\frac{\mathcal{B}(Z(4430)^- \rightarrow \pi^- J/\psi)}{\mathcal{B}(Z(4430)^- \rightarrow \pi^- \psi(2S))} = 0.09_{-0.05}^{+0.18}$.

4.5. Discussions

In Table 4 we summarize all the charged charmoniumlike states reported so far with the mass and width from a simple weighted average of all the available measurements. While the $Z_c(3900)$, $Z_c(4020)$, and $Z(4430)^-$ are established, the two states observed in $B \rightarrow K\chi_{c1}\pi^-$ and the newly observed $Z(4200)^-$ need further confirmation.

Table 4. Summary of the Z_c states.

state	mass (MeV/ c^2)	width (MeV)	comments
$Z_c(3900)^-$	3888.6 ± 2.7	34.7 ± 6.6	Weighted average of Refs. 31–33, 58
$Z_c(4020)^-$	4023.9 ± 2.4	10.2 ± 3.5	Weighted average of Refs. 28, 59
$Z(4050)^-$	4051_{-43}^{+24}	82_{-28}^{+51}	Ref. 55, need confirmation
$Z(4200)^-$	4196_{-30}^{+43}	370_{-110}^{+99}	Ref. 61, need confirmation
$Z(4250)^-$	4248_{-45}^{+185}	177_{-72}^{+321}	Ref. 55, need confirmation
$Z(4430)^-$	4478 ± 20	181 ± 33	Weighted average of Refs. 17, 60

The nature of these states have been discussed for a long time, and there are many proposals [3] which will not repeat. It is obvious that some of these states are close to open charm threshold such as $D\bar{D}^*$ [$Z_c(3900)$], $D^*\bar{D}^*$ [$Z_c(4020)$], $D^*\bar{D}_1$ [$Z(4430)^-$], however, the other states may not be very close to the thresholds.

The understanding of these Z_c^- states and the similar states in the $b\bar{b}$ system [63] may help in the development of the QCD at non-perturbative domain.

5. Summary and perspectives

There are lots of charmoniumlike states observed in charmonium mass region but many of them show properties different from the naive expectation of conventional charmonium states. The BESIII experiment is now producing results on these XYZ states. The observation of the charged charmonium states, $Z_c(3900)$, $Z_c(4020)$, $Z(4430)^-$, and other states, may indicate one kind of the exotic states has been observed.

In the near future, BESIII experiment [12] will accumulate more data between 4.0 and 4.6 GeV for further study; the Belle II experiment [64] under construction, with about 50 ab^{-1} data accumulated, will surely improve our understanding of all these states.

LHCb experiment [13] has produced lots of interesting results, with even more statistics expected, it may further contribute to the XYZ particle study. An immediate effort would be the study of $B \rightarrow K\pi^-\chi_{c1}$ and $B \rightarrow K\pi^-J/\psi$ for a high statistics search for the three Z_c states waiting for confirmation.

PANDA [65], the $p\bar{p}$ annihilation experiment which is designed to study the charmonium and charmoniumlike states, will be able to contribute to the XYZ particle study in a very different way. With a very small beam energy spread, it may measure the line shape of the $X(3872)$ and many other neutral XYZ states; of course, the charged charmoniumlike states can also be produced in company with a charged meson.

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